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Distribution of a Generic Mission Planning and Scheduling Toolkit for Astronomical Spacecraft

Contract NAS5-32800

Annual Progress Report No. 1

For the period 19 October 1994 through 18 October 1995

Principal Investigator:

Dr. Steven C. Kleiner

January 1996

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Greenbelt, MD 20771

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Distribution of a Generic Mission Planning and Scheduling Toolkit
for Astronomical Spacecraft
Contract NAS5-32800
Annual Progress Report No. 1
For the Period 19 October 1994 through 18 October 1995

This is the first annual progress report for our ADP contract "Distribution of a Generic Mission Planning and Scheduling Toolkit for Astronomical Spacecraft."

Work is progressing as outlined in the Statement of Work and proposal for this contract.

A working planning and scheduling system has been documented and packaged and made available to the WIRE Small Explorer group at JPL, the FUSE group at JHU, the NASA/GSFC Laboratory for Astronomy and Solar Physics and the Advanced Planning and Scheduling Branch at STScI.

The package is running successfully on the WIRE computer system and appears to have been well received. The system was recompiled under a different compiler on a different operating system within a few hours and required only a handful of trivial changes. This ease of portability is unusual and speaks well of the coding standards applied to the work. It is anticipated that the WIRE planning and scheduling system will reuse significant portions of the SWAS code in the course of its development.

This scheduling system itself has been successfully run against the spacecraft hardware in end-to-end string tests run in December 1995. In addition to the functionality described in the original proposal, a fully automatic scheduling module has been developed and is being added to the toolkit.

In order to maximize reuse, the code is being reorganized during the current build into object-oriented class libraries with the intent of migration to C++. With this restructuring individual tools which were originally several hundred to a thousand lines of code can now be written in less than a hundred lines. The automatic scheduling tool, for example, is eighty-eight lines long. The class libraries compiled so far include:

| | |
|---|---|
| Constants/ | physical and SWAS-specific constants |
| Event/ | event generation and processing |
| Map/ | mapping attributes |
| Obsmode/ | obsmode manipulation and calculations |
| Quat/ | quaternion manipulation |
| Schedule/ | scheduling functions |
| Segment/ | segment operations |
| Target/ | target procedures |
| Time/ | time manipulation |
| Timeline/ | timeline formatting |

The SWAS planning and scheduling toolkit was described in a talk at the 1994 Astronomical Data Analysis and Software Systems symposium in Baltimore MD. A paper based on that talk has been written and is included in the software distribution.

The only significant difficulty encountered so far is with respect to configuration management. Two versions of the SWAS planning and scheduling toolkit are maintained: a production version for use in actually operating SWAS and an export version for distribution under this contract. Each of these versions generally exists in two forms - a baseline

and a development version. Thus at any given time four very similar but different versions of the code must be managed. This has already led to problems in the export code where directories assigned to the production version were being referenced. This misassignment did not become obvious until the code was transported to a different machine where the production directories did not exist.

The real concern however is the possibility that configuration management problems with the export code cause interference with the production code required for SWAS flight operations. For example the export scheduler is supplied with a dummy target list since it would be inappropriate to distribute the real target list compiled by the SWAS science team. If the dummy target list were inadvertently referenced instead of the real target list, an invalid timeline would be produced for the spacecraft.

The availability of low-cost PCs running UNIX clones such as Linux make it cost effective to preserve the integrity of both versions of the SWAS toolkit by offloading the export version onto a standalone PC. This possibility is being investigated and we expect to request reprogramming of contract funds sufficient to cover the cost of a PC.

Attachments:

(1) The "Readme" page for the general SWAS toolkit description describing the export package.

(2) The "Readme" page giving an overview of the scheduling toolkit.

(3) The "Readme" describing the SWAS graphics demos.

(4) The summary output page from the SWAS automatic scheduling tool. The summary notes that the scheduler was able to use 95.6% of the orbit for science observations. The remaining gaps will be used for required instrument calibration.

(5) The paper describing the SWAS toolkit.

```
/* ---------------------------------------------------------------------- */
              this is file "Readme.swas_distribution"

    SWAS   Submillimeter Wave Astronomy Satellite        NASA GSFC / SAO
         Planning and Scheduling System Distribution  12/95

         corrected 12/29/95 - fixed location of JPLEPH JPL ephemeris file
/* ---------------------------------------------------------------------- */
```

SWAS Planning and Scheduling System Snapshot 12/95

A planning and scheduling system for astronomical spacecraft is available for use by other missions.

The Submillimeter Wave Astronomy Satellite is a NASA Small Explorer spacecraft to be launched in 1996. The 285 kg spacecraft will carry a 0.6m 500 GHz submillimeter wavelength radio telescope to a 600 km altitude. The instrument will observe molecular and atomic line emission from H2O, 13CO, H218O, O2 and CI to study galactic chemistry and star formations at frequencies where the atmosphere is essentially opaque.

The current working version (including source code) of the planning and scheduling system for the SWAS spacecraft is available at the FTP site

cfa-ftp.harvard.edu   in the directory    outgoing/SWAS

or as URL        ftp://cfa-ftp.harvard.edu/outgoing/SWAS

The directory should contain:

```
Readme.swas_dist        the overall SWAS software distribution
Readme.swas_graphics    SWAS graphics demos description
Readme.swas_scheduler   SWAS scheduling sooftware description

swas_paper.ps.Z         postscript paper describing the SWAS scheduler
swas_graphics.tar.Z     graphics displays developed for the scheduler
swas_scheduler.tar.Z    the actual SWAS scheduler
```

README files have been added throughout describing the operation of the code. The code requires only ANSI C and the basic XLIB libraries in order to compile.

The NASA Small Explorer Program emphasizes the development of smaller, cheaper and faster science missions. These constraints required us to develop a small and simple but yet fully functional scheduling system. These same attributes should make the SWAS scheduler suitable as the basis (in part or in whole) for other astronomical scheduling systems or serve as the source of ideas, algorithms or code for other systems. The NASA Astrophysics Data Processing program has recognized the potential utility of the SWAS scheduler and has provided support for the packaging and distribution of the scheduler.

The scheduler included here is a snapshot of the development system as of Winter 1995. The system has been successfully tested against the spacecraft hardware.

Please feel free to email me any questions or comments.


```
 ------------------------------------------------
| The distribution of this scheduling system is |
| supported by NASA/GSFC contract NAS5 - 32800. |
|   All code and text copyright 10/1/95 SAO     |
 ------------------------------------------------
```


Attachment 1

```
/* ------------------------------------------------------------------ */
              this is file "Readme.swas_scheduler"

    SWAS   Submillimeter Wave Astronomy Satellite        NASA GSFC / SAO
         Planning and Scheduling System Distribution  12/95

/* ------------------------------------------------------------------ */
```

Revised version 12/29/95 - corrected error in location of JPLEPH JPL ephemeris file

The directories below contain a snapshot of the planning and scheduling system being developed for the SWAS Small Explorer spacecraft.

## I. Running the scheduler

1. Create a directory at the same level as the existing directorys or change directory to the "test" directory.

2. Type "../bin/schedule" to create a new timeline.

3. Type "../bin/sched_clean" to delete the intermediate product files.

There are two shell scripts in in the "bin directory:

"Schedule" will run all the scheduling tools to create a timeline in the curred working directory.

"Sched_clean" will delete the intermediate product files after the timeline is complete.

The only non-obvious step is for msched, the manual scheduler. You will see a color coded display of rise-and set events. Clicking once on a _colored_ slice will place that event on the schedule. The event is then outlined in red. Clicking on a colored slice in a scheduled event will remove that rise-and-set event from the schedule.

## II. The Scheduling Modules

The scheduler consists of a series of modules:

orbgen generates model orbit data
slpgen generates solar lunar and planetary files
slpsched checks targets for their position w.r.t. the Sun
ggs7 (get guide stars) extracts suitable guide stars for the star tracker
eventgen generates rise-and-set events in the orbital plane for each target
efilt is an event filter which selects the highest scoring events for scheduling
msched3 is the manual scheduler
tlgen5 is the fifth version of the timeline generator

"../catalogs" contains the target list and guide star catalog

## III. Other Modules

| | |
|---|---|
| Constants/ | miscellaneous constants |
| Design/ | file formats, program design |
| Map/ | generate map positions |
| Obsmode.h | list of SWAS observing modes |
| Quat/ | quaternion manipulation library |
| Timeline/ | code to scan timelines |
| allsky/ | misc code for all sky projections |

Attachment 2

```
bin/            scripts for runnning scheduler
bineph/         code to read NASA binary ephemeris files
catalogs/       guide star and target catalogs
check_gs/       guide star selection diagnostics
efilt/          event filter to select best events at each time
eventgen/       generate target rise and set events
ggs7/           get guide stars
maps/           generate map coordinates for data reduction
msched3/        manual scheduler
orbgen/         model orbit generator
psat/           process NASA predictive site acquistion table
sel_mode/       demo graphical user interface for selecting modes
slpgen/         generate solar system positions from JPL ephemeris
slpsched/       planetary positions and Solar viewing constraints
src_misc/       useful miscellaneous source code
test/           empty test directory
tlcheck/        slew angle calculations
tlgen5/         generate timeline from selected events
tools/          coordinate transformation, format target catalogs
```

IV. Compiling the Code
------------------

The included executables are for Sun OS 4.1.3. In general all source code is ANSI C and was compiled with the SUN 'acc' compiler. The GNU 'gcc' compiler with the -ansi switch should work as well. (The '-lm' switch to load the math library might also be needed.) The X window graphics require only the Xlib library, usually specified by the -lX11 argument. Typically the compilation sequence is

```
      acc -o <executable_name> <source1.c>...<sourcen.c> -lX11
```

```
|-----------------------------------------------|
| The distribution of this scheduling system is |
| supported by NASA/GSFC contract NAS5 - 32800. |
|   All code and text copyright 10/1/95 SAO     |
|-----------------------------------------------|
```

Steve Kleiner kleiner@cfa.harvard.edu

Attachment 2

```
/* ------------------------------------------------------------------------ */
          this is file "Readme.swas_graphics"

    SWAS   Submillimeter Wave Astronomy Satellite        NASA GSFC / SAO
        Planning and Scheduling System Distribution  12/95
/* ------------------------------------------------------------------------ */
```

SWAS Graphics

This is a collection of graphics display developed for the SWAS planning and scheduling system. They were used to define and visualize the scheduling problem and will eventually be folded back into the production scheduler used for day to day scheduling.

This SWAS graphics collection consists of the following items:

| | |
|---|---|
| README.swas_graphics | the current file |
| guide_star_movie/ | animation showing the guide star selection algorithm |
| slew_graphics/ | graphics showing the path of slews on the sky |
| viewing_constraints/ | graphics displaying the SWAS viewing constraints |
| year_view/ | a year-at-a-glance planning tool. |

Each directory contains a README file providing more detailed information.


```
|----------------------------------------------|
| The distribution of this scheduling system is |
| supported by NASA/GSFC contract NAS5 - 32800. |
|   All code and text copyright 10/1/95 SAO     |
|----------------------------------------------|
```


Steve Kleiner kleiner@cfa.harvard.edu

SWAS Automatic Scheduler Fri Dec 15 14:20:51 1995

Schedule Summary for 10/25/95

```
targ_read_targets: 100    targets read from 298.targ
                   100    sky targets, 0     cal targets
sched_read_events: 1525   target rise and set events read
```

Scheduling Requirements

| rank | target name | class | priority | duration | days to Sun | orbits requested | orbits available | orbits scheduled |
|---|---|---|---|---|---|---|---|---|
| 1 | S140 | GCC | 1 | 40.09 | 120.0 | 4 | 16 | 4 |
| 2 | W49 | GCC | 2 | 39.62 | 7.0 | 4 | 16 | 4 |
| 3 | W51 | GCC | 2 | 39.55 | 13.1 | 4 | 12 | 4 |
| 4 | S106 | GCC | 2 | 39.64 | 50.1 | 4 | 8 | 4 |
| 5 | DR21 | GCC | 2 | 39.73 | 60.3 | 4 | 4 | 4 |
| 7 | 06056+2131 | GCC | 2 | 39.81 | 168.2 | 4 | 14 | 4 |
| 8 | S252A | GCC | 2 | 39.80 | 168.2 | 4 | 10 | 4 |
| 9 | 06058+2138 | GCC | 2 | 39.76 | 168.2 | 4 | 6 | 4 |
| 10 | S255 | GCC | 2 | 39.73 | 169.3 | 4 | 4 | 4 |
| 42 | G261.6-2.1 | GCC | 4 | 39.84 | 242.8 | 3 | 16 | 3 |
| 52 | DC253.1-1.7A | DCC | 3 | 39.76 | 225.9 | 2 | 13 | 2 |
| 53 | DC267.4-7.5 | DCC | 3 | 40.03 | 259.7 | 2 | 11 | 2 |
| 62 | DC253.3-1.6 | DCC | 4 | 39.73 | 226.1 | 2 | 9 | 2 |
| 63 | CG1 | DCC | 4 | 40.10 | 226.5 | 2 | 7 | 2 |
| 64 | ESO210 | DCC | 4 | 40.02 | 259.7 | 2 | 5 | 2 |
| 65 | DC267.7-7.4 | DCC | 4 | 40.02 | 260.3 | 2 | 3 | 2 |
| 71 | RZ_SGR | STA | 3 | 36.61 | 11.3 | 2 | 1 | 1 |

Schedule Summary

| class | number of observations | time (hrs) | time (percentage) |
|---|---|---|---|
| GCC | 41 | 20.6 | 77.3 % |
| DCC | 12 | 4.4 | 16.6 % |
| STA | 1 | 0.4 | 1.6 % |
| GAP | 12 | 1.2 | 4.4 % |
| TOTAL | 66 | 26.6* | 100.0 % |

* Note that schedule may exceed 24 hours at this stage.

Attachment 4

# A Graphical Planning and Scheduling Toolkit for Astronomical Spacecraft

S.C. Kleiner

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**Abstract.**

A small yet powerful planning and scheduling toolkit has been built for the SWAS Small Explorer spacecraft. It makes extensive use of graphics to illuminate the planning and scheduling process.

The simple design, minimal resource requirements and easy extensibility of the SWAS planning and scheduling toolkit should make it useful for other space astronomy missions. A release of the toolkit for general use is planned shortly.

## 1. The SWAS Mission

The Submillimeter Wave Astronomy Satellite is a 500lb NASA Small Explorer spacecraft to be placed in low Earth orbit by a Pegasus XL launch vehicle in 1995. It will investigate the chemistry and energetics of star forming molecular clouds via the simultaneous observation of the $O_2$, CI, $H_2O$ and $^{13}CO$ spectral lines in the 487-557 $\mu$m (538-615 GHz) range. The mission was proposed by the Smithsonian Astrophysical Observatory in Cambridge MA, which has the responsibility for the scientific component of the mission. The mission is managed by the Goddard Space Flight Center.

The science instrument consists of a 0.65m dual receiver radio telescope with an acousto-optical spectrometer backend. The spectrometer is read out every two seconds for the life of the mission, producing 100MB of raw data every day. SWAS will observe 50 – 100 targets a day. The minimum planned mission duration is two years.

SWAS is the first astronomical Small Explorer, a series of missions to be developed under a "smaller, cheaper, faster" imperative. The turnaround time for SWAS, for example, should be about five years from acceptance of proposal to launch. The SAO Science Operations Center responsible for the development and operation of the science ground system consists of six scientists, including Principal Investigator Gary Melnick and Project Scientist John Stauffer. The planning toolkit described below was designed and written in two years by the SWAS Planning Scientist.

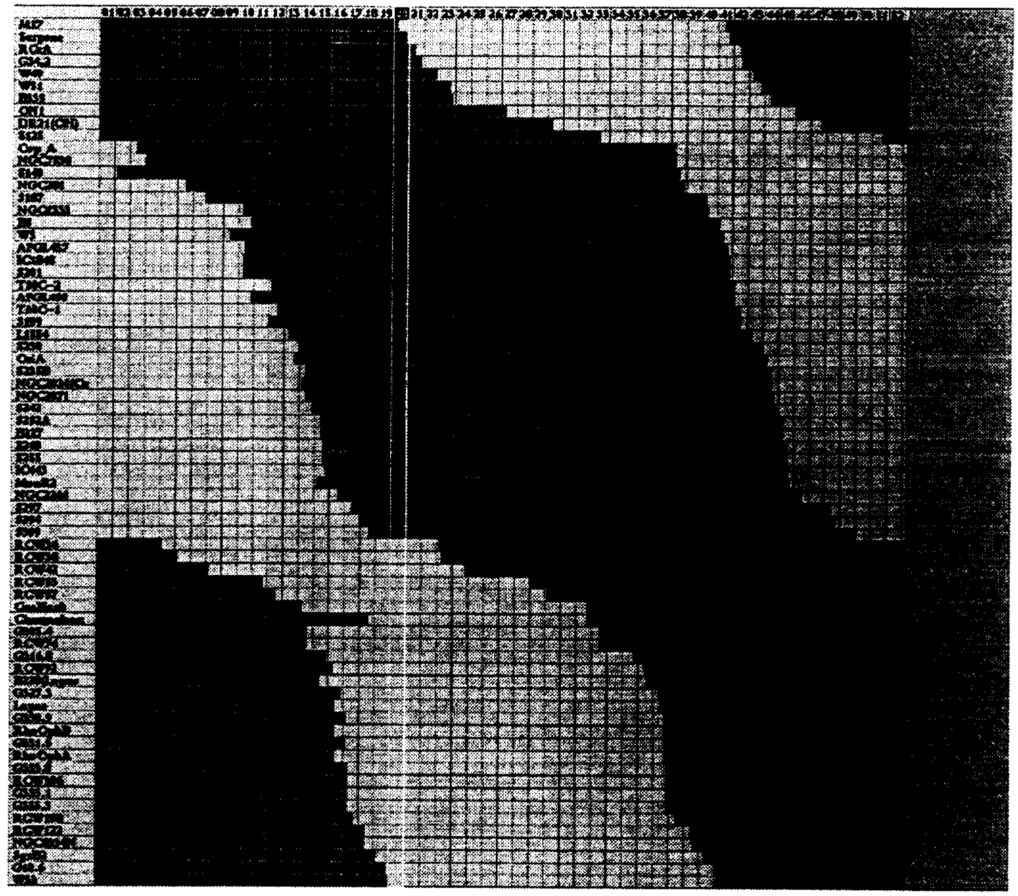

Figure 1. One Year Planning Display for Week 20. Fifty-two weeks run across the top of the display. The shading indicates days when a target is visible or when Earth, Moon or Sun constraints are violated.

## 2. The SWAS Planning and Scheduling Toolkit

This stand-alone toolkit provides all the planning and scheduling functions for the SWAS spacecraft, including processing of the NASA predictive ephemerides, target visibility calculations, long range planning and short term (orbit-to-orbit) scheduling, slew constraint checking, nominal roll calculations, guide star selection, and generation of detailed spacecraft timelines for conversion into command uploads. The toolkit displays its calculations graphically and makes extensive use of coordinate transformations in order to avoid any brute force calculations, a concept recognized by David Koch of NASA/Ames in his development of a prototype scheduler for SWAS. A new guide star catalog for CCD star trackers has also been developed (Stauffer 1993). The toolkit is currently generating timelines to support prelaunch testing of the flight operations facilities at GSFC.

The toolkit has a minimalist design, consisting of independent tools or 'filters' which operate on a single stream of scheduling events. Events include orbital ascending node crossings, the rising or setting of a target above the

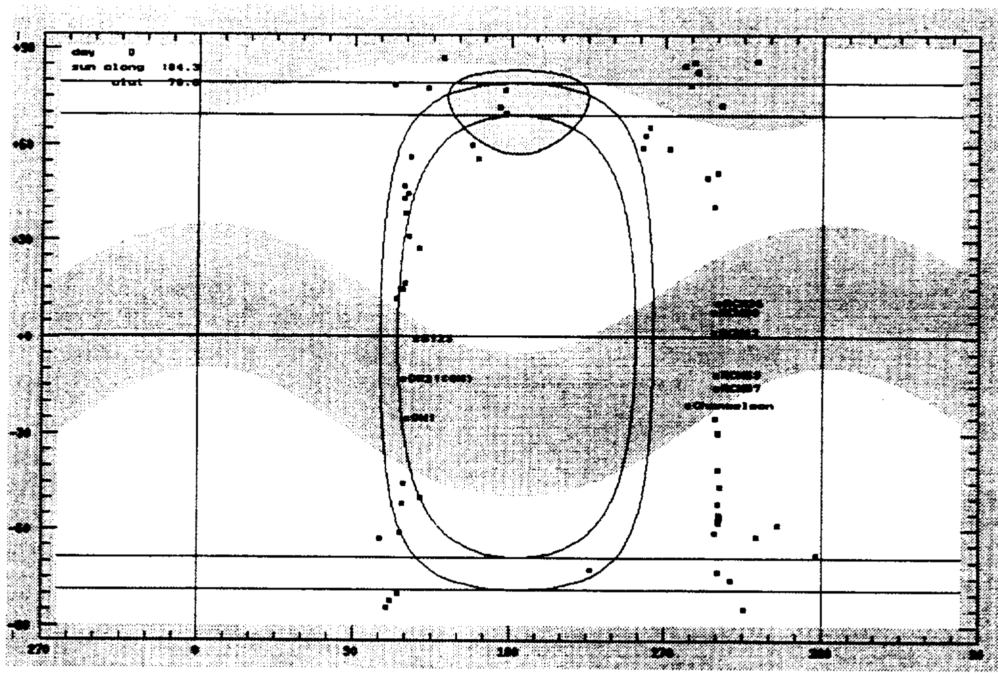

Figure 2. Pointing Constraint Display. The horizontal scale is orbital longitude, the vertical scale orbital latitude. The labeled targets in the central swath satisfy the Sun, Earth and Moon pointing constraints.

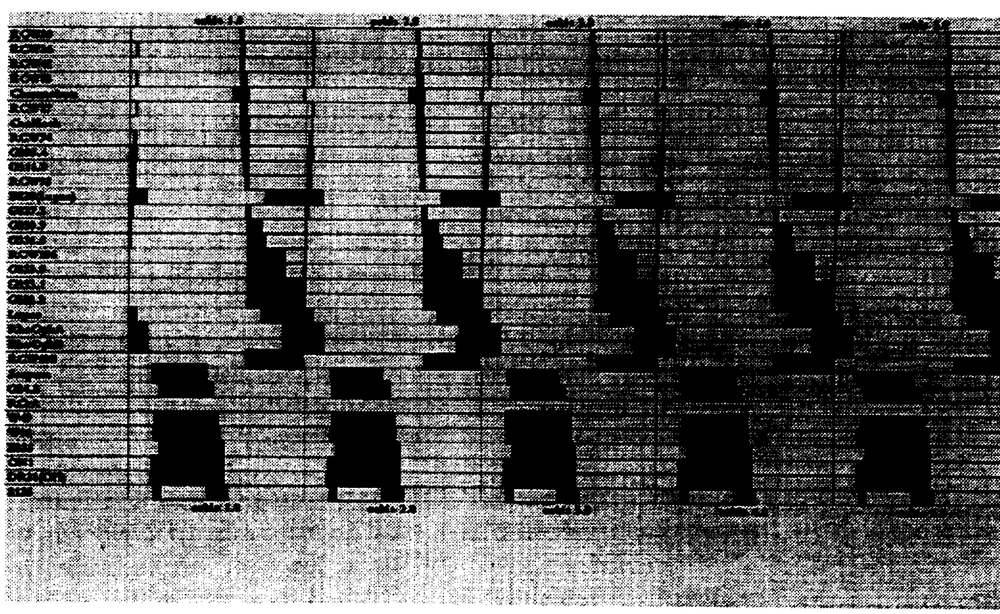

Figure 3. Scheduler Display for Five Orbits. The rectangles are target rise-and-set events shaded according to their scientific value and scheduling efficiency. The heavily outlined targets have been selected for scheduling.

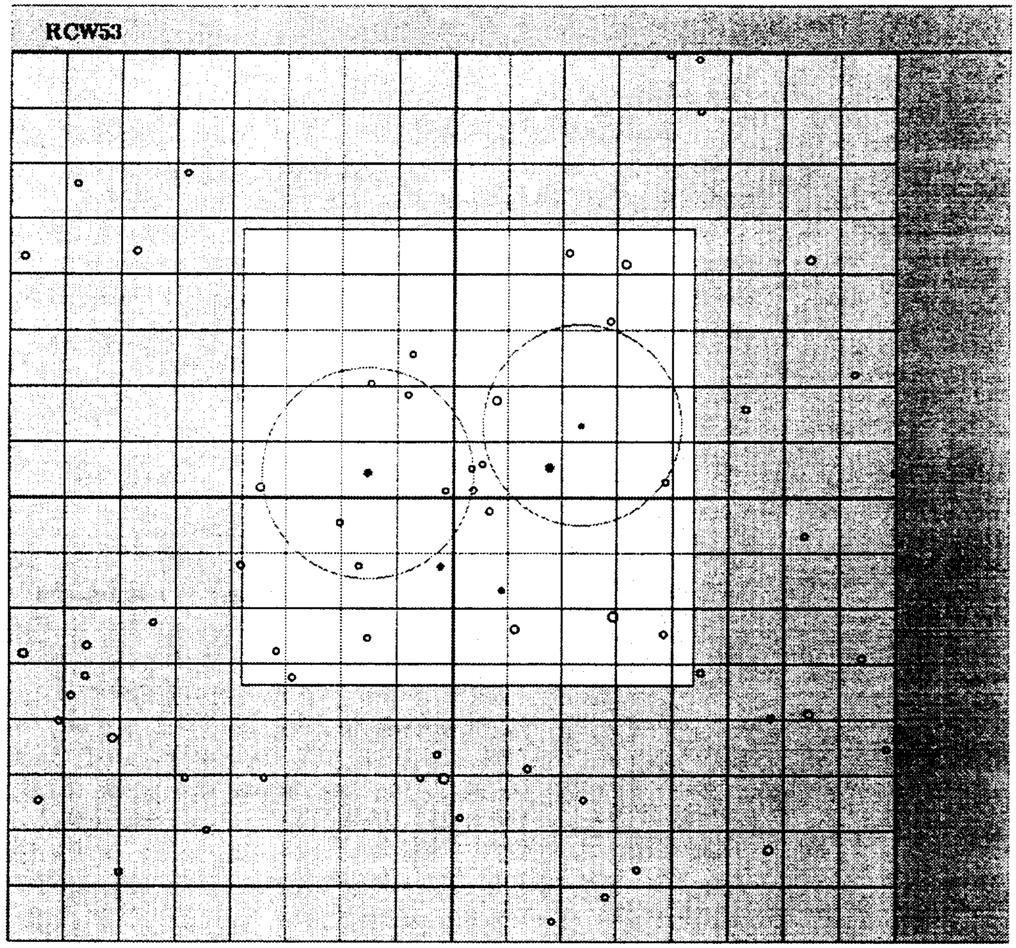


Figure 4. Guide Star Selection Display. Grid spacing is 1°. The central square is the star tracker field of view. Open circles denote potential guide stars, filled circles the selected guide stars.

Earth horizon and the entry and exit of a target into pointing avoidance regions around the Sun and the Moon. The toolkit is extended by defining new events and adding the appropriate filters. Since SWAS uses the planets for calibration, the toolkit can also schedule planetary pointings. Calculations are done in orbit relative time rather than absolute time to minimize the effect of uncertainties in predictive ephemerides. The toolkit is fast enough that the same tools are used both for long range planning and short term scheduling. The planning toolkit consists of about a dozen tools, less than ten thousand lines of ANSI C code in total. It makes only plain Xlib calls for the graphics and does not make any Unix system calls.

## 3. SWAS Planning and Scheduling Graphics

Figures 1 - 4 were color graphics which have been reduced in size and converted to greyscale. Their legibility suffers greatly as a result.

Figure 1 is a planning display showing target visibilities over the course of the year. The lighter bands running from top left to bottom right are days in which the target is too close to the Sun. (SWAS has 75-120° Sun, 40° Earth and 15° Moon pointing constraints.) We have found by experience that long term planning is driven primarily by the position of the Sun with respect to the target. Therefore, for any given week targets going into the Sun soonest are given the highest scheduling priority.

Figure 2 shows pointing constraints as seen from the orbital plane. The Sun is near the north orbital pole and the lighter swaths are regions of the sky which violate the SWAS Sun pointing constraint. The small black squares are potential targets, but only those which satisfy the pointing constraints at some time in the orbit are labeled by the software.

Figure 3 is the interactive scheduling display showing five orbits. Each rectangle represents the rise and set of a target during an orbit. The rectangles are filled and shaded according to the target's scientific interest and scheduling efficiency. The scheduling scientist uses a mouse to point and click to select or deselect a target for inclusion into the timeline sent to the spacecraft, as indicated by their heavy black outline around selected targets.

Figure 4 displays the potential guide stars around the target RCW53. The stars are taken from the guide star catalog created for the BASG CT601 star tracker aboard SWAS. Open circles are the guide stars from the catalog, the filled circles are the guide stars which have been selected by the planning and scheduling toolkit. The guide stars are selected on the basis of their brightness and their distance from the edge of the star tracker FOV and from other guide stars which might be confused with the intended guide star. The two large circles identify the base guide stars which are aquired first after a slew. The radii of the circles denote the size of the slew induced pointing error which can tolerated before confusing the base star with another star.

## References

Stauffer, J. 1993, "Creation of a Guide Star Catalog for the BASG CT-601 Startracker", SWAS Technical Memorandum

87 018-00

# REPORT DOCUMENTATION PAGE

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**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*

Work is progressing as outlined in the proposal for this contract. A working planning and scheduling system has been documented and packaged and made available to the WIRE Small Explorer group at JPL, the FUSE group at JHU, the NASA/GSFC Laboratory for Astronomy and Solar Physics and the Advanced Planning and Scheduling Branch at STScI.

The package is running successfully on the WIRE computer system. It is expected that the WIRE will reuse significant portions of the SWAS code in its system.

This scheduling system itself was tested successfully against the spacecraft hardware in December 1995. A fully automatic scheduling module has been developed and is being added to the toolkit.

In order to maximize reuse, the code is being reorganized during the current build into object-oriented class libraries.

A paper describing the toolkit has been written and is included i n the software distribution.

We have experienced interference between the export and production versions of the toolkit. We will be requesting permission to reprogram funds in order to purchase a standalone PC onto which to offload the export version.

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